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II. GENERATION OF POWER AND OTHER STEAM USES

By John Whitmore

> "It is not enough to know that the total cost of power for the month is so many dollars, of which so much is fixed charges, so much fuel, etc. . . . Individual unit costs should be determined for electricity, high- and low-pressure steam, refrigeration, compressed air and other services. These should be charged to consuming departments on the basis of quantities actually used, as determined by meter readings." (Editorial, *Power*, May 12, 1931.)

The British thermal unit is stated to be the heat required to raise the temperature of one pound of water one degree Fahrenheit, but this is slightly qualified even within the range of temperatures to which it is practically applicable. Throughout the scale the heat required to raise the temperature of one pound of water one degree Fahrenheit changes gradually. Also it is said that "the mean B. t. u. is defined as 1/180 part of the heat required to raise the temperature of one pound of water from 32° to 212°." Practically the definition first stated above may be regarded as actual up to 212° and somewhat beyond that temperature.

The British thermal unit has also its mechanical equivalent, which is stated as 778 foot-pounds. The commercial engine-horse-power is fixed at 33,000 foot-pounds per minute. This gives 42.416 B. t. u. as the equivalent of one engine-horse-power-minute, or 2545 B. t. u. as the equivalent of one engine-horse-power-hour.

The kilowatt of electrical energy equals 1.34 horse-power or 44,220 foot-pounds per minute. The kw. minute is therefore the equivalent of 57 B. t. u. and the kw. hour the equivalent of of 3414 B. t. u.

The horse-power being defined as 33,000 foot-pounds per minute, there are in the determination of horse-power developed two factors, pressure and distance, and the pressure being first expressed in pounds per square inch, it follows that this is to be multiplied by the square inches of surface upon which the pressure is effective. In the reciprocating engine power is developed by the pressure of steam upon the piston in the cylinder. This pressure changes throughout the piston-stroke, and an instrument called a steam engine indicator * is used to determine "the mean effective pressure." From the mean effective pressure and the piston-travel in feet per minute, the horse-power developed is calculated.

If power is then transmitted throughout a plant by means of shafting, belting, and pulleys, it is against the determination of horse-power developed by the engine that the economy of its uses must be measured. If the engine drives an electric generator or air compressor, its output of power is accounted for by these uses, and thereafter it is the output of electric current or compressed air that is to be accounted for.

Steam turbines are said to be "most efficiently used direct connected to electrical generators, centrifugal pumps, centrifugal compressors, and ship propellers." † If a steam turbine is direct connected to another machine, the two are treated as a unit. If, as is most often the case, the turbine drives an electrical generator, the cost of the whole operation of turbine and generator, determined in a single account, is the cost of the electrical output, and it is this output that is to be accounted for. It is exactly the same thing if a reciprocating engine drives an electric generator.

Either reciprocating engines or turbines may be condensing or non-condensing.

The non-condensing engine or turbine uses steam to generate power, and then delivers the steam as exhaust steam, at a pressure and temperature which are lower proportionately to the efficiency of the engine or turbine, but potentially of the same value, proportionately to its remaining heat content. The power developed in this case is limited by the back-pressure of the exhaust steam.

The condensing engine or turbine is equipped with condensing apparatus, by means of which the exhaust steam is immediately condensed, and a vacuum substituted for the back-pressure of the non-condensing engine or turbine. Under these conditions there is a considerable increase in the power developed, but no steam

* "The steam engine indicator is a form of recording pressure gauge, arranged to be attached to the cylinder of a steam engine so as to draw a curve representing the pressure within the cylinder at every point in the stroke." By means of it, the engineer calculates the mean effective pressure in the cylinder, in pounds per square inch. This multiplied by the area of the piston in square inches, multiplied by the piston speed in feet per minute, and the result divided by 33,000, gives the indicated horse-power developed (Suplee's *Mechanical Engineering*, pages 650 and 651).

† Marks' *Mechanical Engineers' Handbook*, p. 1203

survives for any further uses. The condensing of the steam is effected by means of large quantities of cold water. The latent heat of evaporation is given up when the steam is condensed, and in the engine or turbine condenser it is absorbed by the condensing water and is lost. If the exhaust steam is not condensed, but delivered as steam for further uses, the latent heat of evaporation may possibly almost all be serviceable for heating purposes. This depends, of course, upon there being work of heating for which it can be used.

The heat in steam, as generated in the boilers, is therefore put to two quite distinct uses: it may be converted into power, or it may be transferred simply as heat, and it is variously so transferred to water for the boilers, to the atmosphere for necessary heating, and to various materials in manufacturing processes. Steam, as generated in the boilers may be used to produce power only, or it may be used as live steam for heating purposes only. Or it may be used first to produce power, and then as exhaust steam for heating.

It may be used more than once at successively lower pressures to produce power in multiple stage turbines and compound engines. With this the accounting is scarcely concerned, inasmuch as the turbine or engine is a unit and a single account covers its total operation. There is however another way in which the same steam is used more than once to produce power. The exhaust steam from a reciprocating engine may be used to operate a low-pressure turbine. *

The heat content of exhaust steam is commonly spoken of as being about 90% of the heat content of the steam as it enters the engine. On page 1179 of Marks' *Handbook*, there is a table "Comparative results of steam engine tests: Saturated vs. Superheated Steam," which indicates the following:

	Initial pressure (abs.) pounds per sq. inch	Superheat deg. Fahr.	Average B. t. u. consumed per I. h. p. hr.	Recovery
Simple non-condensing engines	150–180	0	24,780	10.27%
	150–180	260	19,620	12.97%

*"Low-pressure turbines are those designed to utilize low-pressure steam, usually exhaust steam from other apparatus. . . . Installations having large reciprocating engines can greatly increase the overall steam economy and output by the addition of low-pressure turbines taking the steam from the engines at pressures slightly above atmosphere. The additional capacity thus secured is usually about 100%." Marks' *Mechanical Engineers' Handbook*, p. 1227. See also *Industrial Management*, April, 1928: "The Steam Turbine points new ways to factory savings," Standerwick.

These figures are said to represent the "best current practice." The figure of 90% in ordinary good practice is therefore presumably fairly close.

Inasmuch as the value of exhaust steam is to be considered in comparison with the gain in production of power by operating the engine condensing (less the expense of operating the condenser and all apparatus in connection therewith), it may be noted here that the same table indicates the following in regard to condensing engines:

	Initial pressure (abs.) pounds per sq. inch	Superheat deg. Fahr.	Average B. t. u. consumed per I. h. p. hr.	Recovery
Simple condensing engines	120–150	0	19,200	13.25%
	120–150	260	14,400	17.7%
Compound condensing engines	120–180	0	17,340	14.65%
	120–180	260	13,770	18.5%

With so great waste in the condensation of steam after its use in engines of even the highest efficiency, and with the possibility of an even greater waste in operating engines non-condensing and having insufficient uses for the exhaust steam delivered, there is in every manufacturing plant the very important problem of balancing the generation of power and the provision of steam for other uses. The matter assumes the most various aspects and leads to the most various conclusions. Much has been written about so-called "by-product power," meaning power generated by the use of steam which is thereafter used for other purposes. Plainly such power is not a by-product in any strict sense. It is the immediate product of the steam in its first state, and reduces its value in an inevitable measure.* But the enthusiasm for "by-product power" may be contrasted with the fact that some important plants purchase power and operate boilers solely for process steam.†

Apparently the most important single means of balancing the

*The idea is sometimes expressed that the steam economy of the engine is not of very real importance if there are further uses for the steam. This may be true as long as steam direct from the boilers is passed through a reducing valve, giving a loss which might apparently just as well be borne in the engine operation. This seems to be indicated in an article entitled "Don't waste exhaust steam" in *Power*, August 25, 1931, but I am sceptical of its holding true through the inevitable fluctuations of demand for process steam. I should anticipate that a strict accounting would show the contrary. The higher the efficiency of the engine, the lower the process steam demand can fall before it will result in exhausting to the atmosphere. In any case the two matters are better not confused. It is safer to insist upon clean economy in each separate process.

†An interesting example of the operation of boilers for process steam alone, purchasing all power, is described in an article entitled "How Kelvinator handles power" in *Industrial Management*, June, 1929.

generation of power and the provision of steam for other uses is the "bleeder" turbine, permitting the extraction of steam after it has been used to generate power, but before its usefulness for this purpose is exhausted.*

Also power may be produced partly by condensing and partly by non-condensing engines or turbines; and it may be partly purchased and partly generated within the plant. Under certain conditions of intermittent loads a steam accumulator may be used.† An internal combustion engine has an obvious possible place in plans for balancing production of power and production of process steam.

An essential provision for the accomplishment of the steam accounting is a chart of all steam transmission lines from the generation of steam in the boilers, through all its uses, showing the direction of the flow, the normal pressure, the locations of flow meters and of any reducing valves, or in long steam lines, possibly superheaters. This chart must be blue-printed, and all metered or calculated quantities and average pressures and temperatures of steam transferred in the month must be stated on a copy of the print at the close of the month by the power department for the use of the power accountant.

Having now all the quantities and average pressures and temperatures taken for use and delivered for further use in the month, there remains the pricing of the steam under all conditions. I have suggested that steam from the boilers be charged to all its original uses at a standard price per million British thermal units.

The departments and processes using exhaust steam can take it at the standard price per million British thermal units, if this will result in their heating work costing them no more than the same heating work would cost them accomplished in any other way. If their needs for process steam are intermittent so that they could not normally be provided for without waste in the intervals of low demand, and if the power plant arrangements

* "Extraction or bleeder turbines are high-pressure turbines which permit the extraction of some of the low-pressure steam from any of their stages. These turbines are used where quantities of low-pressure steam are needed constantly or intermittently. . . . Some installations require turbines which will utilize low-pressure steam from various sources when there is an excess of this low-pressure steam, and will automatically supply low-pressure steam when there is a deficiency." Marks' *Mechanical Engineers' Handbook* (1930), p. 1228.

† "A steam accumulator is a device for storing the heat energy of steam. A large mass of water in a suitable vessel is heated by mixing with steam. When there is an excess of steam, this excess is condensed in the accumulator with a consequent rise of its temperature and pressure. Then during intervals of deficiency of steam, the deficit is drawn from the accumulator. As the pressure in the accumulator drops, the hot water is vaporized at the expense of the stored heat." Marks' *Mechanical Engineers' Handbook* (1930), p. 358. See also p. 1227 of same. Also *Industrial Management*, December, 1930, p. 1166, "The use of a steam accumulator is common practice in the paper industry."

are such that waste has actually to be borne, a higher price than the standard price per million B. t. u. may be perfectly proper. If the power plant arrangements are such that exhaust steam is not wasted in the intervals of low process steam demand, then no more than the standard price per million B. t. u. should be charged.

The engine or turbine and the manufacturing department must be regarded as quite independent units, which will deal with each other if it is for their mutual advantage, while neither will allow the unit cost of its own product to be increased for the benefit of the other. This is a necessary condition of the full responsibility of each department for its own costs.

The operation of a non-condensing engine is justified if according to the most careful calculation that can be made, the credit to the engine operation through charges to departments and processes for exhaust steam priced according to strict rules, will reduce the unit cost of power below what it would be operating a condensing engine.

Assuming that there is loss of exhaust steam and that the question consequently arises whether this loss is to be borne entirely by the engine operation, without compensation through a higher price for steam actually used by manufacturing departments, such question might be answered, first, by considering and calculating what the cost of process steam actually used would be per million B. t. u. if a low-pressure boiler were operated solely for process steam; and second, by considering whether heat other than steam heat could be used and what its cost would be. All the steps that I am suggesting seem to be absolutely necessary to determine the most economical means of operation. It is no accidental coincidence that they are at the same time the steps that are necessary in order to accomplish a true accounting for the expenditures. I do not believe it is too much to say that the two will always be found to coincide. As I proceed I shall have occasion to point out other examples of this.

Extracted or bled steam may also be credited to turbine or compound engine* at the standard price per million available B. t. u. contained in it, but not with the effect of increasing the cost of the unit of power developed. The engine or turbine

* Compound engines: Receiver steam (between high and low-pressure cylinders) used for heating: The receiver may deliver part of its steam for heating or process work. Marks' *Mechanical Engineers' Handbook*, p. 1172.

having nothing to gain by the extraction of steam, must not be permitted to lose thereby. If in its construction additional cost is incurred to enable it to deliver, or if in its operation lowered efficiency occurs through delivering extracted steam, the latter must be credited at a price which will compensate for these disadvantages. This will result in a true showing of the respective economies, inasmuch as there is no expense of process steam in this connection when the demand ceases, nor relatively increased expense when the demand is low.

The million B. t. u. in exhaust steam may have the same value as a million B. t. u. in live steam, if the exhaust is to be used for process purposes but not if it is to be used again to generate power. In the latter case the initial pressure is an important factor in the value. The exhaust from a reciprocating engine may be charged to process at the standard price per million B. t. u., but if it were so charged to a low-pressure turbine, the engine would show a low cost for power and the turbine a very high cost. The first would bear perhaps ten per cent. of the steam cost, and the second ninety per cent. Marks' *Mechanical Engineers' Handbook* (p. 1227) says the additional capacity secured by the addition of the turbine is usually about 100%. The low-pressure turbine operates condensing.*

Wherever a turbine receives exhaust steam from a non-condensing engine it will be best to endeavor to cover the two in a single account, so that no entry transferring exhaust from one to the other will arise. This is simple in the case of a low-pressure turbine operating solely with exhaust steam. I think it may also be done where a bleeder turbine takes exhaust steam intermittently. If under any conditions it should be necessary to credit exhaust to non-condensing engine and debit it to the turbine, this would necessarily be done at a price sufficiently below the standard price per million B. t. u. to make the condensing loss fall proportionately on the total power developed from the steam which ultimately goes to the turbine condenser.

The accounting is then to be continued in exactly the same manner as before, if a department using either live or exhaust or extracted steam delivers it again for any other purpose; or if the process steam lines deliver condensate having a valuable heat content for return to the boilers. In the article "How Kelvi-

* Low-pressure turbines should operate exhausting into high vacua. Marks' *Handbook* p. 1227.

nator handles power" in *Industrial Management*, June, 1929, already referred to, it is stated that "85% of the steam is returned to the heater as condensate at a comparatively high temperature."

The operation of a non-condensing engine is justified by the average credit that it can receive for exhaust steam throughout the year, and there will inevitably be considerable variations from month to month and from season to season. I think it is advisable that non-condensing engine or turbine shall in each month receive the average calculated credit, so that the cost of power shall not be raised or lowered as the uses for exhaust steam are greater in one month than in another. At the same time the departments and processes must be charged with steam as they use it. An intervening account may be used to effect both these purposes. The average calculated credit for exhaust can in each month be given to engine or turbine and the same debited to such intervening account, and actual consumptions credited thereto and debited departments and processes. Such an account would carry a steam balance in suspense temporarily, operating to equalize the steam credits to engine or turbine throughout the year, leaving the power cost figures, to this extent, more actually comparable from month to month.*

Whenever steam, or power in any form, is to be credited to one account and debited to another, metering is of course desirable. Whenever metering is not provided for, and calculations have to be used, the operation of the accounts will provide a check upon such calculations, for if they are incorrect one cost is overstated and another understated, and this unless it is slight will probably be recognizable. Rarely at first can one get all the metering of steam, or even of electric current, that one could desire, and whenever meterings are not available, and the power engineer can furnish calculations, one must work with these, and if all that is possible is done with these in the meantime, the results will before long surely justify all metering that is necessary.

Metering moreover is not serviceable only for the construction of the accounts and for accuracy in the determination of costs. Probably in every place where it is useful for these purposes, it is also useful, and of course in many places absolutely necessary, for operating control. Metering of steam and power to manu-

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* With effective provision for balancing production of power and production of steam for process and heating the necessity for the accounting procedure outlined in this paragraph would of course disappear.

facturing departments is also essential to their economical use. It has been said that manufacturing departments are great wasters of power. Two things are necessary to cure this. First, the charges to the departments must be unquestionable, both as to quantities and prices; and, second, there must be standards against which the economy of the consumption can be measured. As to the first of these I am trying to suggest in this article how it is to be accomplished; the second I must consider in a later article.

I will close the present article with a summary of the accounting procedure necessary to the operations from the point at which steam is delivered by the boilers, to its uses in generating power, or its delivery to departments for heating and process work.

We have in the preceding article assumed that steam is metered from the boilers, and that inasmuch as it is inevitably to some extent thereafter divided for different uses, there shall be sufficient metering (minor uses being sometimes calculated) so that closely correct quantities shall be charged to each and especially that correct quantities shall be charged to each engine and turbine. There must then be an account or a series of accounts for these. If condensing engine or turbine is operated singly, and the steam supplied to it by the boilers is not subsequently reduced by extraction or added to by supply from any other source, and if its individual output of power is recorded, these conditions give a perfectly simple account and determination of the unit cost of power developed. If however there is valuable heat in the water from the condensing of the exhaust a credit for this is to be provided.

If a prime mover simply drives a generator or air compressor, a single account will cover both to give the unit cost of electric power or compressed air. If two or more generators, with their prime movers, are operated in conjunction with each other to give a single output of electric power, a single account may be kept for their total operation.* Where generators are connected in parallel, power being transferred between them as necessary, a single account is the only procedure possible.

If the exhaust steam from a reciprocating engine is used to drive a low-pressure turbine, a single account for the two will I think always be desirable. The power output of the turbine may be credited to the account at a standard price and the balance

* Just as a single account may be kept for two or more boilers, but in either case, a separate account for each unit is desirable, if input and output of each are known. Or a single account may be kept with a subsidiary record to show the performance of each unit.

of the account will then be the cost of the power output of the engine.

If a bleeder turbine takes exhaust steam from a non-condensing engine intermittently, I believe a single account for the two is still desirable. Such an account would be debited with the expenses of both units, and with the live steam furnished to both units; and would be credited with exhaust steam from the engine or bled steam from the turbine delivered to the process steam lines, and would be credited with the total power developed.

The term "a single account" as used in the foregoing paragraphs means a single principal account, which may have as many subsidiary accounts as are convenient to effect any desired classification of the expenses or credits. But these subsidiary accounts are merely intermediate and at the end of the month are closed into the single principal account.

When operating expenses are common to two or more accounts, such expenses must be divided between the accounts in proportions determined in consultation with the power engineer.

I have dealt fully with the pricing of exhaust and extracted steam supplied to heating and process lines and delivered to departments and uses, and with offsetting credits for steam or condensate delivered by them. Steam so delivered must be metered at the point of delivery to the department to be held responsible for the economy of its use. From the month's report of meterings and any supplementary calculations, as above described, and with the prices determined according to the rules herein suggested, or necessary adaptation of them, all the necessary journal entries can be made at the close of the month without any difficulty at all.

The following determinations should be stated monthly, and tabulated in comparative form for the months throughout the year:

1. The electrical current purchased in the month, its cost in total and per kilowatt hour.
2. The electrical current generated in the month, its cost in total and per kilowatt hour.
3. The cubic feet of free air compressed in the month, its cost in total and per 1,000 cubic feet.
4. The mechanical power developed in the month to be transmitted by shafting, belting and pulleys, its cost in total and per horse-power hour developed.

5. The following steam summary:

	Lbs.	B. t. u. contents (millions)	Standard cost per million B. t. u.	Amount
Generated in boilers.				
Delivered to condensing prime movers.				
Delivered to other uses, not yielding exhaust steam for further use.				
Total not yielding exhaust steam.				
Balance.				
Consumed in generating power.				
Delivered for heating and manufacturing processes.				
Lost to atmosphere.				

It is here the final item that is in grave need of being stated in quantity and money figures wherever the condition which it refers to exists. In the course of this article I have pointed out that exhaust steam may under certain conditions be chargeable to processes at a price in excess of the standard cost per million B. t. u. Nevertheless I think it best to use only standard costs in the foregoing steam summary. A notation may be made of the difference in the charge for steam delivered for heating and manufacturing processes, if there is such a difference.

It is my intention in a final article to consider the accounts in relation to the transmission and application of power.